# Monte-Carlo simulation of ion distributions in a gas cell for multinucleon transfer reaction products at LENSHIAF spectrometer

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**Abstract**

The multinucleon transfer (MNT) reaction is one promising way to produce neutron-rich heavy nuclei and even super heavy nuclei and attracts more and more attentions theoretically and experimentally. A low energy nuclear structure spectrometer called LENSHIAF specific to the MNT reactions will be designed and constructed in the ongoing big project HIAF in China. In the LENSHIAF spectrometer, the most challenge part is how to collect and stop efficiently the high-energy MNT products into the gas cell. By using Monte-Carlo method, the geometry of the gas cell, the thickness of the titanium window/degrader, and the optimal gas pressure filled in the gas cell have been calculated and estimated. For neutron-rich nuclei around N=126 from $^{136}$Xe+$^{198}$Pt reaction, with a titanium window/degrader with a thickness of 2.5–3.5 $\mu$m, a cylindrical helium gas cell with a length of 0.6 m and a diameter of 1.2 m can satisfy the requirements to stop the target-like fragments. For heavier and super heavy nuclei from $^{238}$U+$^{238}$U reaction, with a 5–8 $\mu$m thick titanium window/degrader, the cylindrical gas cell has to be as big as a length of at least 1.6 m and a diameter of 1.6 m.

*Keywords:* neutron-rich nuclide, multinucleon transfer, radioactive ion beam, HIAF, Monte-Carlo method

## 1. Introduction

Approximately half of the nuclei in nature heavier than iron are considered to be synthesized by the rapid neutron capture process (*r*-process), which proceeds under the stellar environment of high neutron densities and high temperatures [1]. The remnants on the *r*-process path decay to the valley of the $\beta$ stability and the observed solar *r*-abundance distribution shows a peak around the mass number of 195, which is considered to originate from the waiting point nuclei with the "magic" neutron number N=126. The experimental information on those nuclei is extremely scarce for Z≤80 because those nuclei cannot be produced by conventional fusion, fission, and fragmentation methods. The multinucleon transfer (MNT) reaction becomes an alternative method to produce neutron-rich nuclei far from stability. Cross sections of nuclei from $^{64}$Ni+$^{207}$Pb [2], $^{136}$Xe+$^{208}$Pb [3], $^{136}$Xe+$^{198}$Pt [4] have already been measured experimentally. At GANIL in France, Watanabe et al. [4] measured the absolute cross sections for isotopically identified products formed in MNT in $^{136}$Xe+$^{198}$Pt system and corroborated that the MNT reactions are the optimum method to populate and characterize neutron-rich isotopes around N=126.

The MNT reactions are also attractive for the study of superheavy nuclei synthesis. Synthesizing neutron-rich heavy and super-heavy nuclei and studying their characteristic properties is one of the important current focal points in both experimental and theoretical nuclear science. Up to now, the technique which is typically used to synthesis heavy isotopes with Z>100 is fusion of a heavy target nucleus with a light to medium projectile nucleus. Because the cross sections become lower and lower as the interested isotopes go further towards the northeast on the chart of the nuclides, for example, ~0.5 picobarns [5] for producing oganesson (Z=118), and the compound nuclei produced are still neutron deficient relative to the line of $\beta$ stability, alternative reaction mechanisms, such as MNT reactions, are proposed and explored. Many reaction systems, such as $^{238}$U+$^{238}$U [6, 7], $^{238}$U+$^{232}$Th [8], $^{238}$U+$^{248}$Cm [9], have been studied experimentally.

Nowadays, the MNT reaction between two heavy nuclei is believed to be one promising way to produce neutron-rich heavy nuclei and super heavy nuclei for investigating the structure properties of nuclei in the region far from the $\beta$ stability. It has been studied extensively for a long time both theoretically and experimentally. See references in Ref. [10].

In the ongoing big project HIAF (High Intensity heavy-ion Accelerator Facility) [11], a Low Energy Nuclear Structure spectrometer called LENSHIAF specific to MNT reactions will be designed and constructed [12]. Fig. 1 shows the conceptual design schematically. In this spectrometer, the researches will be concentrated on the synthesis and identification of new

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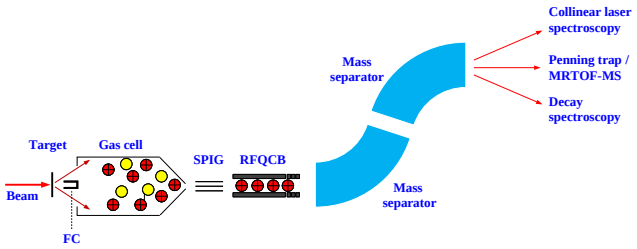


Figure 1: Conceptual design of the LENSHIAF spectrometer.

neutron-rich nuclei, and on the study of their nuclear structure and decay properties. In the very preliminary design, primary beams provided by the accelerator impinge upon a rotating target to produce neutron-rich nuclei by MNT reactions. Those high-energy ions are stopped in the gas cell by adjusting the thickness of a titanium degrader and the gas density filled in the gas cell. The ions are transported to the exit of the gas cell by combining electrostatic and radio-frequency fields and then extracted out of it by an electrostatic field and supersonic gas flow. The extracted ions are transported through a differential pumping section by a sextupole ion guide (SPIG) and then injected into a radio-frequency quadrupole cooler and buncher (RFQCB). After cooling and accumulating in the RFQCB, ion bunches are ejected, accelerated to a kinetic energy of a few keV. The ions are separated by one/two mass separators according to their mass-to-charge ratio and the ions of interest are sent to the successive workstations for collinear laser spectroscopy, decay spectroscopy and mass measurements by Penning traps [13] and multi-reflection time-of-flight mass spectrometer (MRTOF-MS) [14–16].

Among all the processes and devices mentioned above, the most challenge part is how to collect and stop efficiently the high-energy products from the MNT reactions into the gas cell. The geometry of the gas cell, the thickness of the titanium window/degrader and the optimal gas pressure filled in the gas cell are the parameters we try to study first. In this paper, the simulation process by using Monte-Carlo method and the results are reported.

## 2. Simulation details and results

We chose two projectile-target systems as examples for the simulation. One is the $^{136}$Xe+$^{198}$Pt (target) system at a beam energy of 7.98 MeV/A. Watanabe et al. [4] have already measured the absolute cross sections for isotopically identified products formed in MNT in this system. Another is the $^{238}$U+$^{238}$U system at a beam energy of 7.0 MeV/A. This system has been investigated extensively as early as late 1970s at GSI in Germany [6] and many experimental data are available for the comparison between the experimental measurements and theoretical predictions.

### 2.1. Double differential cross sections of the MNT reactions

To describe the MNT process in low-energy heavy-ion collisions and understand the dynamical mechanism in heavy-ion collisions, some semiclassical and microscopic models are proposed. The semiclassical models such as the dinuclear system (DNS) [10], GRAZING [17], and complex WKB (CWKB) [18] have shown reasonable success in predicting the production cross sections of neutron rich heavy nuclei in MNT reactions. The microscopic dynamics models such as the time-dependent Hartree-Fock (TDHF) model [19] and the improved quantum molecular dynamics (ImQMD) model [20–23] have been developed to study the dynamic characters and energy dissipation of MNT reactions. The ImQMD model is a semiclassical microscopic dynamics model which includes the mean-field and nucleon-nucleon collisions as well as the Pauli principle and is successfully applied to heavy-ion fusion reactions at energies near the Coulomb barrier and intermediate-energy heavy-ion collisions. The dynamical evolution of the heavy-ion collisions in both reaction systems has been calculated by using the ImQMD model [21, 22]. The de-excitation process of primary fragments has been treated with the GEMINI code [24] for the $^{136}$Xe+$^{198}$Pt system, and with the HIVAP code [25] for $^{238}$U+$^{238}$U.

The double differential cross sections of $^{200}$Os from the $^{136}$Xe+$^{198}$Pt system and $^{243}$U from $^{238}$U+$^{238}$U are shown in Fig. 2. The reason to choose $^{243}$U for the simulation will be mentioned later. Obviously, they behave rather differently. Most of produced $^{200}$Os ions eject around the outgoing angles of 60°with total kinetic energies of ~150 MeV, which correspond to the residues produced from the target-like primary fragments, while for $^{243}$U ions, most of them eject in the outgoing angles of 35–50°with total kinetic energies of 600–1000 MeV, which correspond to the residues produced from both the target-like and projectile-like primary fragments.

### 2.2. A simple model

A simple model for the simulation is shown in Fig. 3. It includes a target, a titanium foil and a cylindrical gas cell. In the simulation of $^{200}$Os, the thickness of $^{198}$Pt target is chosen to be 1.3 mg/cm$^2$ as same as that in Ref. [4] and it is divided into 6 layers artificially to consider the energy losses of the produced $^{200}$Os ions. While for the $^{243}$U ions, the thickness of $^{238}$U target is chosen to be 95 mg/cm$^2$ after considering the possible optimal combinations of the target and the titanium degrader. In the front of the gas cell, a titanium foil is placed as a window to seal the gas cell and accept the injected ions and also acts as a solid degrader. The distance between the target and the window is set to 10 mm to leave a space for a possible rotating target system. The cryogenic gas cell is cooled down to 90 K and filled with helium gas with a pressure of 80 mbar. It corresponds a gas density with a pressure of 260 mbar in the room temperature, which is typically used in the gas cells.

We used SRIM code [26] to calculate the stopping powers/ranges and then used these calculated values as “experimental” data for reality. By using their large collection of stopping power data, Paul and Schinner [27] compared those data to various stopping power tables and computer codes to estimate the reliability of these tables and codes. They found that SRIM worked fairly well for all ions and for all energies. Unfortunately, the SRIM code cannot deal with the isotopes with Z>92

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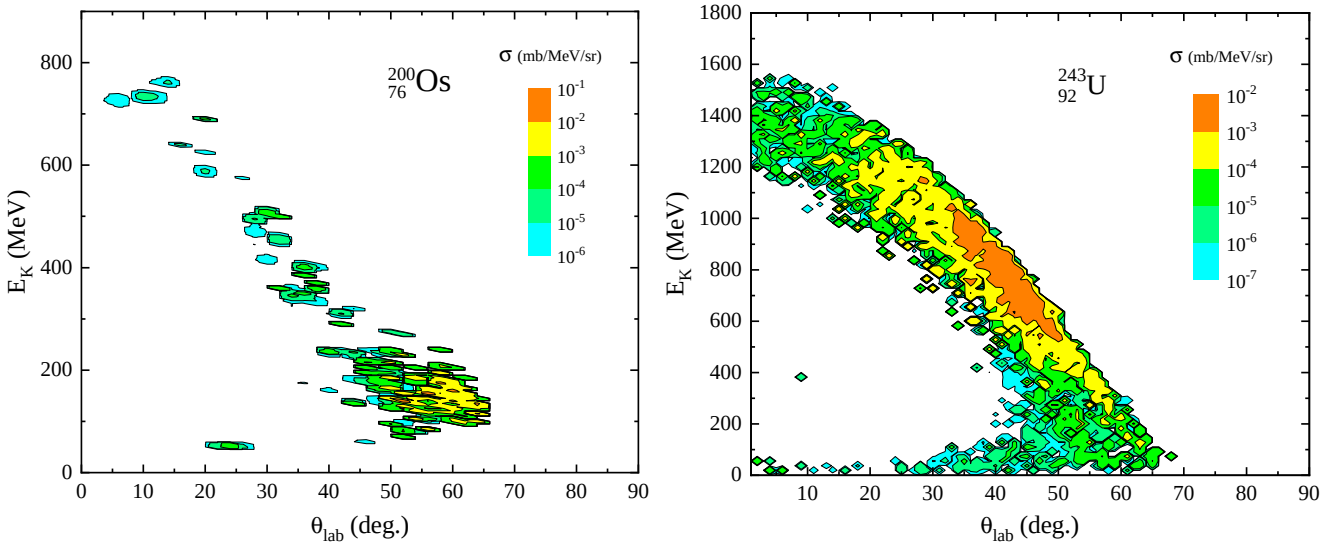


Figure 2: Double differential cross sections of $^{200}$Os in the $^{136}$Xe+$^{198}$Pt system (left) and $^{243}$U in $^{238}$U+$^{238}$U (right).

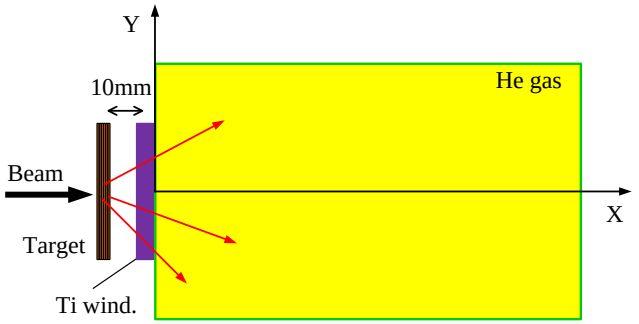


Figure 3: A simple model for the simulation including a target, a titanium foil and a cylindrical gas cell.

and thus the $^{243}$U is chosen in the simulation of $^{238}$U+$^{238}$U system. We use Monte-Carlo method for the simulation.

### *2.3. Ion distribution of $^{200}$Os stopped in the gas cell*

Fig. 4(a) and (b) show the calculated distributions of $^{200}$Os ions in the gas cell with 2.5 and 5.0 $\mu$m thick titanium window, respectively. The temperature of the helium gas is 90 K and the pressure is 80 mbar. Fig. 4(c) shows the transmission efficiencies as varying the thickness of the titanium window, where the transmission efficiency is defined as the ratio of the counts of $^{200}$Os ions stopped in the gas cell and that produced in the MNT reactions. Obviously, a thicker titanium window can absorb more energies of the ions and thus shorten the stopping range in the gas cell. But the transmission efficiency goes down because many ions are stopped in the window. To keep high transmission efficiency and reasonable strength, a titanium window with a thickness of 2.5–3.5 $\mu$m should be chosen. Thus the cylindrical gas cell with a length of 0.6 m and a diameter of 1.2 m can satisfy the requirements to stop the target-like fragments from the $^{136}$Xe+$^{198}$Pt system.

### *2.4. Ion distribution of $^{243}$U stopped in the gas cell*

Fig. 5 shows the calculated distributions of $^{243}$U ions in gas cell. The temperature of the helium gas is 90 K for all the cases. Because the $^{243}$U ions eject from the target with a rather higher energy and a smaller outgoing angle than the $^{200}$Os ions, the transmission efficiency is quite high (>80%) for the cases we considered. Fig. 5(a)-(c) correspond to the gas cell with 3, 7 and 10 $\mu$m thick titanium window, respectively. The pressure in the gas cell is 80 mbar. It shows that for a reasonable thickness of titanium window of 5–8 $\mu$m, the cylindrical gas cell for $^{238}$U+$^{238}$U system has to be very big, as big as a length of at least 1.6 m and a diameter of 1.6 m.

Of course, we can reduce the size of the gas cell by increasing the helium gas density. Fig. 5(d)-(e) show the calculated results, in which the thickness of the titanium window is kept as 7 $\mu$m. The former corresponds to a gas pressure of 120 mbar and the latter 160 mbar. The size of the gas cell decreased indeed, but higher gas pressure may introduce difficulties when transporting the stopped ions to the exit of the gas cell due to longer transport time, higher radio-frequency voltages and so on.

## 3. Summary

In the ongoing big project HIAF in China, the LENSHIAF spectrometer specific to the multinucleon transfer (MNT) reactions will be designed and constructed. The geometry of the gas cell, the thickness of the titanium window/degrader, and the optimal gas pressure filled in the gas cell have been studied by using Monte-Carlo method.

For neutron-rich nuclei around N=126, we took $^{200}$Os from 7.98 MeV/A $^{136}$Xe+$^{198}$Pt reaction as an example. The simulation shows a titanium window/degrader with a thickness of 2.5–3.5 $\mu$m should be chosen to keep high transmission efficiency and reasonable strength, and a cylindrical helium gas

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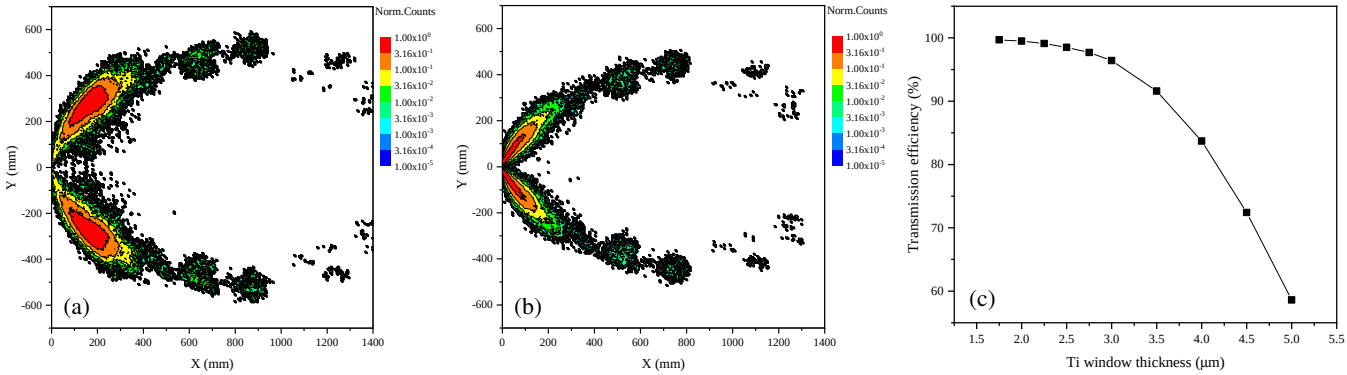


Figure 4: (a)-(b) Calculated distributions of $^{200}$Os ions in the gas cell with a 2.5 and 5.0 $\mu$m titanium window, respectively. (c) Transmission efficiency as a function of the thickness of the titanium window. The distance between the target and the window is 10 mm. The temperature of the helium gas is 90 K and the pressure is 80 mbar.

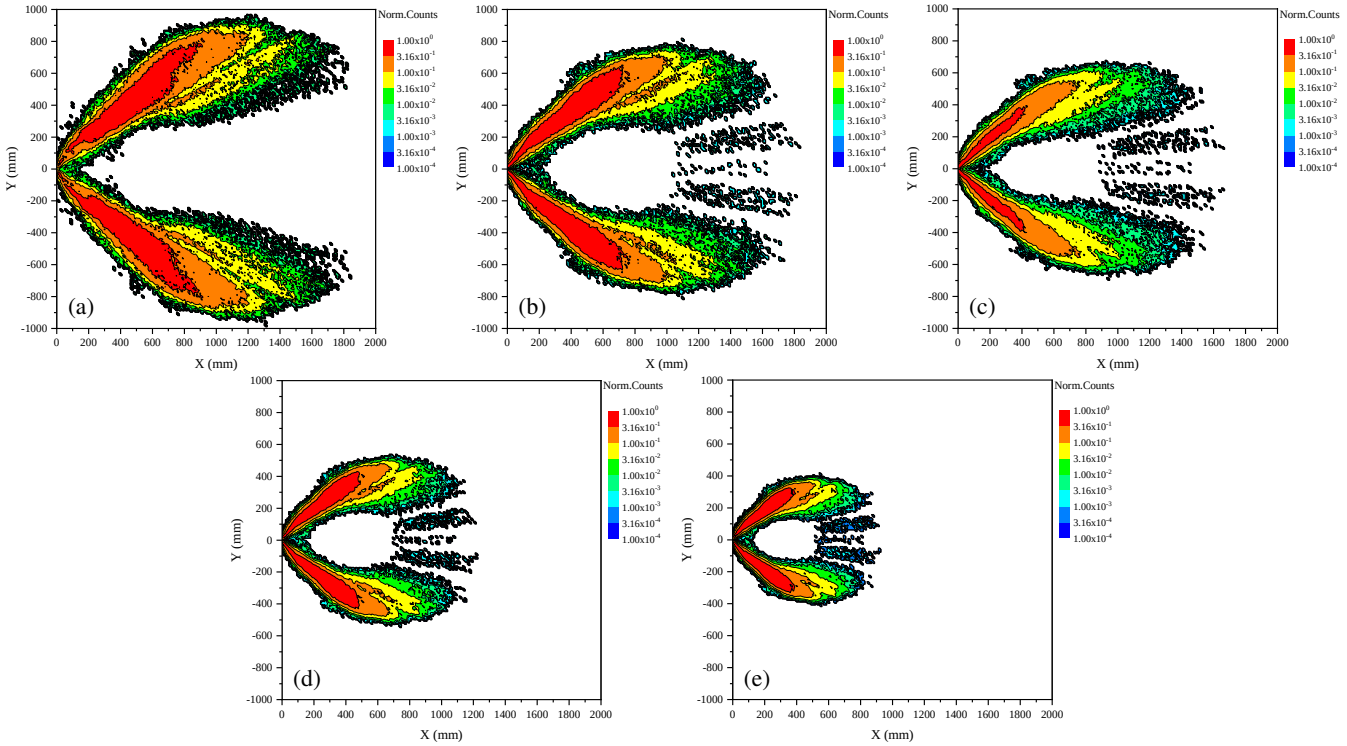


Figure 5: Calculated distributions of $^{243}$U ions in the gas cell. The distance between the target and the window is 10 mm. The temperature of the helium gas is 90 K. (a)-(c): The titanium window has a thickness of 3, 7 and 10 $\mu$m, respectively. The pressure in the gas cell is 80 mbar. (d)-(e): The titanium window has a thickness of 7 $\mu$m. The pressure is 120 and 160 mbar, respectively.

cell with a length of 0.6 m and a diameter of 1.2 m can satisfy the requirements to stop the target-like fragments.

For heavier and super heavy nuclei, we had to choose $^{243}$U from 7.0 MeV/A $^{238}$U+$^{238}$U reaction as an example due to the limitation of SRIM code. The simulation shows that for a reasonable thickness of titanium window of 5–8 $\mu$m, the cylindrical gas cell for $^{238}$U+$^{238}$U system has to be very big, as big as a length of at least 1.6 m and a diameter of 1.6 m. Although we can reduce the size of the gas cell by increasing the helium gas density, higher gas pressure may introduce difficulties when transporting the stopped ions to the exit of the gas cell due to longer transport time, higher radio-frequency voltages and so on.

It seems that we have to consider two different gas cells for these two different reaction systems. The methods to transport the stopped ions to the exit of the gas cell and then extract the ions out of it with a high total efficiency are needed to be studied very carefully in a near future. How to separate/get rid of the primary beam and scattered ions from the MNT products is still an open question.

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